# A Robust PID Autotuning Method for Steam/Water Loop in Large Scale Ships

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**Abstract:** During the voyage of the ship, disturbances from the sea dynamics are frequently changing, and the ship's operation mode is also varied. Hence, it is necessary to have a good controller for steam/water loop, as the control task is becoming more challenging in large scale ships. In this paper, a robust proportional-integral-derivative (PID) autotuning method is presented and applied to the steam/water loop based on single sine tests for every sub-loop in the steam/water loop. The controller is obtained during which the user-defined robustness margins are guaranteed. Its performance is compared against other PID autotuners, and results indicate its superiority.

***Keywords:*** PID autotuner, Steam power plant, Steam/water loop, Multi-input and multi-output, Modulus margin, Robustness

## 1. INTRODUCTION

The steam/water loop in large scale ships has the characteristics such as being a complex structure, with large number of devices and strong coupling in input-output variables. Hence, it is difficult to design a single, satisfactory controller for this system. There is few work about the control for large scale ship systems. During the voyage of the ship, the disturbance from the sea dynamics are changing and frequently the ship operation mode is also variable (Liu et a., 2016). Therefore it is meaningful to design a robust controller for steam/water loop, as this is the main energy consumer on the ship, with great impact on overall system's stability. There are mainly four sub-loops in the steam/water loop, including i) water level control loop in the drum, ii) water level control in condenser, iii) pressure and water level control in deaerator, iv) pressure control in exhaust manifold.

Most works on steam/water loop are mainly about the boiler-turbine system, in which the outputs are power output, drum water level and drum water pressure. Many advanced control strategies have been developed in this system, such as: de decentralized PID control (Dimeo and Lee,1995; Tan et al., 2004; Garrido et al., 2009; Sayed et al., 2015), sliding mode control (Ghabraei et al., 2015; Moradi et al., 2012; Mahmoodabadi et al., 2015), robust control (Kwon et al., 2014; Mathiyalagan et al., 2015), and model predictive control (Wu et al., 2014; Kong et al., 2015; Zhang et al., 2017).

To design a controller for the water level in the condenser, it is necessary to take into account the coupling influence between condenser water level and deaerator water level. (Wang et al., 2015; Zhang et al., 2005). In the sub-loop of pressure and water level control in deaerator it is also necessary to consider the coupling effect between pressure and water level. PID neural network decoupling control was designed for the control of deaerator pressure and water level (Wang et al., 2014). Exhaust manifold is the pipeline system existing in the steam/water loop, and other auxiliary machines have to work under the pressure condition of exhaust manifold. However, the gas used in deaerator comes from the exhaust manifold. Thus, there is a strong coupling relationship between the exhaust manifold pressure and deaerator pressure which makes it difficult to develop an acceptable controller. Due to the complexity of the steam/water loop, it is difficult to obtain the model of the entire system. A PID autotuning method named KC autotuner is applied to the steam/water loop which by-passes the burden of a full modeling procedure. The KC autotuner is based on defining a 'forbidden region' for robustness in the Nyquist plane according to user-defined specifications. By designing an adequate PID controller, the Nyquist curve of the process will be changed to fulfil the robustness specified by the user.

The paper is structured as follows. The steam/water loop is descripted in section 2. In section 3, the detailed theory of KC autotuner is introduced. The results and conclusions are given in section 4 and section 5, respectively.

## 2. DESCRIPTION OF THE STEAM/WATER LOOP

The steam/water loop is shown in Fig. 1, where the red line indicates steam loop and the green line indicates water loop. Major equipment in this loop includes boiler, condenser, deaerator, exhaust manifold and pumps. The steam/water loop works as follows. Firstly, the feed water is supplied into the boiler after being heated in the economizer. Secondly, due

 

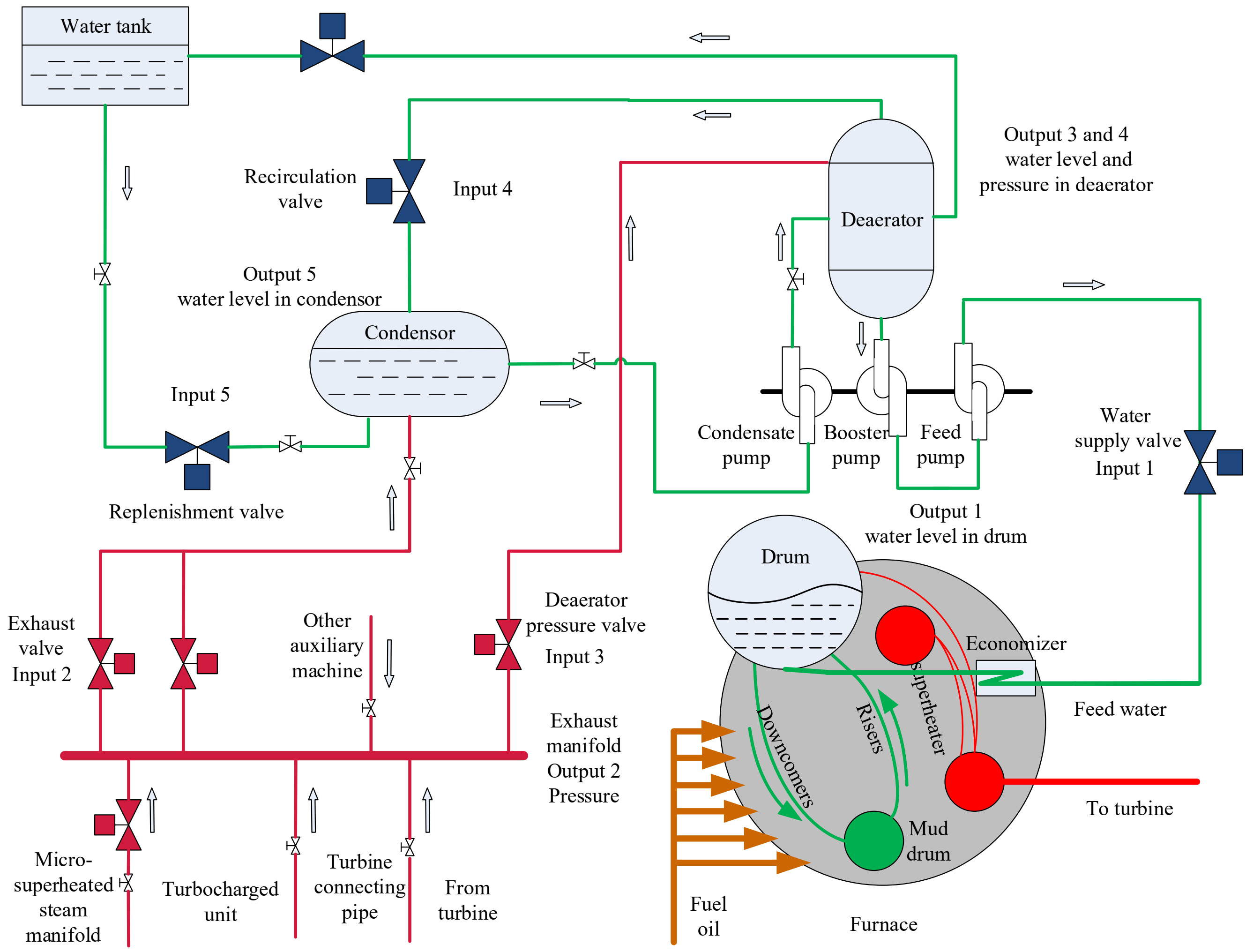


Fig. 1. Scheme of steam/water loop

to the higher density of the feed water, it will flow into the mud drum. Then, after being heated in risers under the burning of the fuel, the feed water turn into saturated mixture of water and steam. Thirdly, after the steam is separated from the mixture, the steam will be heated in superheater and used in steam turbine. Finally, the used steam will be condensed, deoxygenated and pumped to the boiler once again (Drbal et al., 2012). In this system, the interaction exists in many loops, i) drum water level and deaerator water level ii) deaerator pressure and deaerator water level; iii) deaerator pressure and exhaust manifold pressure; iv) deaerator water level and condenser water level.

**Table 1. Parameters used in steam/water loop**

| Output variables | Operating point | Range | Units |
|---|---|---|---|
| Drum water level | 1.774 | [1.2-2.2] | m |
| Exhaust manifold pressure | 0.132 | [0.12-0.14] | MPa |
| Deaerator pressure | 30.51 | [24.2-37.4] | KPa |
| Deaerator water level | 0.6839 | [0.49–0.88] | m |
| Condenser water level | 0.4979 | [0.35-0.66] | m |

In the steam/water loop, there are five variables (the water level in drum, pressure in exhaust manifold, water level and pressure in deaerator and water level in condenser) that need to be controlled by manipulating five variables (the opening of water supply valve, exhaust valve, deaerator pressure valve, recirculation valve and replenishment valve). The ranges of the input variables are all 10%~100%, and the operating point are all 50%. The outputs used in this paper are shown in Table 1 (including ranges and initial operating point of output variables).

## 3. CONTROL DESIGN FOR STEAM/WATER LOOP

In this part, the detailed theory about KC autotuner is introduced (De Keyser et al, 2017). Fig. 2 illustrates the main idea of this autotuner as to move a point B on the Nyquist curve of process $P(j\omega)$ to another point A on the Nyquist curve of the loop $L(j\omega)=P(j\omega)C(j\omega)$ through the PID controller indicated by $C(j\omega)$. The “forbidden region” in Fig. 2 is obtained according to system performance requirements, for example a specific robustness or loop minimum phase and gain margin. In order to have a good performance, the Nyquist curve of loop $L(j\omega)$ should be tangent to this “forbidden region”. Hence, the slope of ‘forbidden region’ and slope of loop $L(j\omega)$ should be the same. The tuning

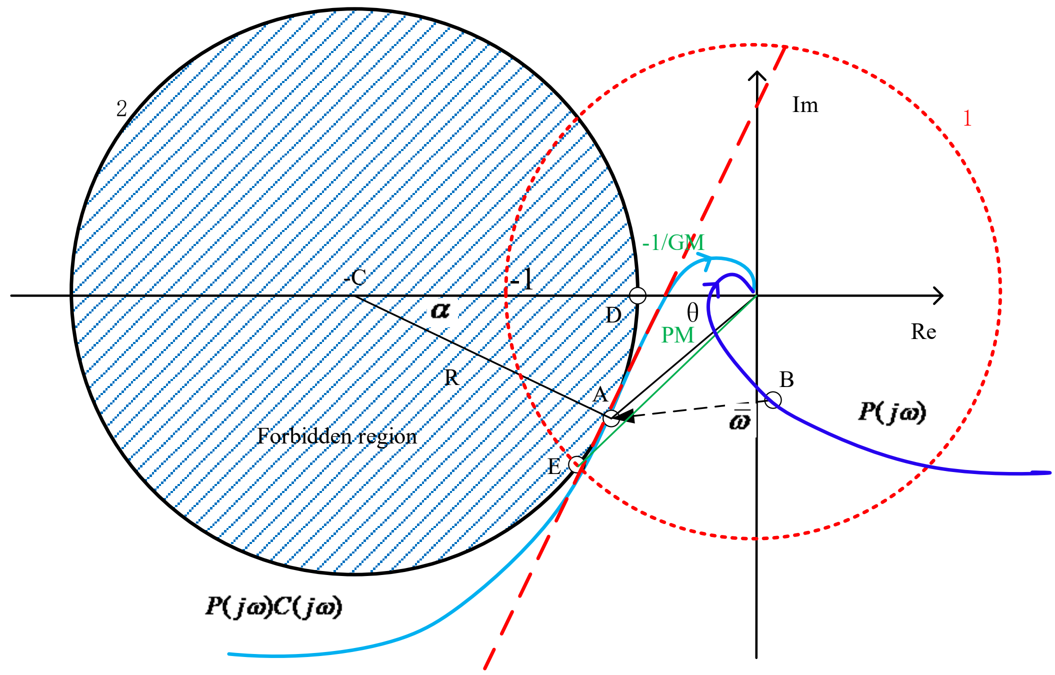


Fig. 2. Graphic illustration of autotuning principle. See text for description.

procedure can be summarized as follows.

1) Select a frequency $\varpi$ ($\varpi$ is usually critical frequency, but might be different)
2) Perform sine tests on the steam/water loop
3) Define a 'forbidden region' in the Nyquist plane according to the loop minimum phase and gain margin
4) For each point on the region border (for $\alpha$ from 0° to 90°), calculate PID controller
5) Find the point where the loop *L(jω)* is tangent to the 'forbidden region'
6) The PID controller from step 5) is final.

In Fig. 2, the point D and point E are obtained according to loop minimum phase and gain. D is the intersection of gain margin with negative real axis. E is the intersection of phase margin with unit circle. According to points D and E, the circle can be calculated as:

$$Forbidden\ region:\ (\mathrm{Re}{+}\mathrm{C})^2+\mathrm{Im}^2=R^2 \tag{1}$$

$$\begin{aligned} &D \Rightarrow\ (\text{-}1/GM+C)^2=R^2 \\ &E \Rightarrow\ (-\cos PM+C)^2+(-\sin PM)^2=R^2 \end{aligned} \tag{2}$$

and the centre and radius of the forbidden region are are calculated as follows:

$$\mathrm{C}{=}\frac{GM^2-1}{2GM(GM\cos PM-1)};\ \mathrm{R}{=}\mathrm{C}\text{-}\frac{1}{GM} \tag{3}$$

and the slope on the point A:

$$\left.\frac{d\,\mathrm{Im}}{d\,\mathrm{Re}}\right|_{\alpha}=\frac{-\mathrm{Re}+C}{\mathrm{Im}}=\frac{\cos\alpha}{\sin\alpha} \tag{4}$$

The derivative from *L(jω)* to *ω* is calculated, from which the slope of loop *L(jω)* can be obtained.

$$\begin{aligned} \frac{dP(j\omega)C(j\omega)}{d\omega} &= P(j\omega)\frac{dC(j\omega)}{d\omega}+C(j\omega)\frac{dP(j\omega)}{d\omega} \\ &= \frac{d\,\mathrm{Re}_{PC}}{d\omega}+j\frac{d\,\mathrm{Im}_{PC}}{d\omega} \\ &\Rightarrow\ \Rightarrow \left.\frac{d\,\mathrm{Im}_{PC}}{d\,\mathrm{Re}_{PC}}\right|_{\varpi} \end{aligned} \tag{5}$$

with $\varpi$ the specified frequency. At the point A, the following equation is obtained.

$$M_A e^{j\varphi_A}=M_{PC}(j\varpi)e^{j\varphi_{PC}(j\varpi)} \tag{6}$$

It can be rewritten as:

$$\begin{cases} M_A=M_{PC}(j\varpi)=M_P(j\varpi)M_C(j\varpi) \\ \varphi_A=\varphi_{PC}(j\varpi)=\varphi_P(j\varpi)\varphi_C(j\varpi) \end{cases} \tag{7}$$

According to the typical form of PID controller

$$\begin{aligned} C(j\omega) &= K_P(1+\frac{1}{T_i j\omega}+T_d j\omega) \\ &= K_P+jK_P\frac{T_dT_i\omega^2-1}{T_i\omega} \end{aligned} \tag{8}$$

The modulus and phase of the controller are as follows.

$$M_{C(j\omega)}=K_P\sqrt{1+(\frac{T_dT_i\omega^2-1}{T_i\omega})^2} \tag{9}$$

$$\varphi_{C(j\omega)} = \text{atan}(\frac{T_d T_i \omega^2 - 1}{T_i \omega}) \tag{10}$$

From the point A on 'forbidden region', the modulus and phase can be calculated as follows.

$$\begin{aligned} M_A &= \sqrt{R^2 \sin^2\alpha + (C - R\cos\alpha)^2} \\ &= \sqrt{C^2 + R^2 - 2CR\cos\alpha} \end{aligned} \tag{11}$$

$$\tan(\varphi_C + \varphi_P) = \frac{R\sin\alpha}{C - R\cos\alpha} = \frac{\tan\varphi_C + \tan\varphi_P}{1 - \tan\varphi_C \tan\varphi_P} \tag{12}$$

hence we have:

$$\tan\varphi_C = \frac{R\sin\alpha - \tan\varphi_P (C - R\cos\alpha)}{\tan\varphi_P R\sin\alpha + (C - R\cos\alpha)} \tag{13}$$

Let:

$$F = \frac{R\sin\alpha - \tan\varphi_P (C - R\cos\alpha)}{\tan\varphi_P R\sin\alpha + (C - R\cos\alpha)} \tag{14}$$

And considering the relationship of $T_i=4T_d$, the $T_d$ can be calculated as:

$$T_d = \frac{F + \sqrt{F^2 + 1}}{2\varpi} \tag{15}$$

Substituting $T_d$ to equation(7), $K_p$ can be obtained as:

$$K_p = \frac{M_A}{M_P(j\varpi)\sqrt{1+F^2}} \tag{16}$$

Therefore the item of $C(j\varpi)$ and $\left.\frac{dC(j\omega)}{d\omega}\right|_{\varpi}$ can be calculated as follows:

$$C(j\varpi) = K_p(1 + j\frac{T_d T_i \varpi^2 - 1}{T_i \varpi}) = \frac{M_A}{M_P(j\varpi)\sqrt{1+F^2}}(1 + jF) \tag{17}$$

$$\begin{aligned} \left.\frac{dC(j\omega)}{d\omega}\right|_{\omega=\varpi} &= K_p(-\frac{1}{jT_i\varpi^2} + jT_d) \\ &= jK_p(\frac{T_d T_i \varpi^2 + 1}{T_i \varpi}) = j\frac{M_A}{M_P(j\varpi)\varpi} \end{aligned} \tag{18}$$

The $P(j\varpi)$ and $\left.\frac{dP(j\omega)}{d\omega}\right|_{\omega=\varpi}$ can be obtained according to sine test (De Keyser et al., 2016). Hence, the $\left.\frac{d\,\text{Im}_{PC}}{d\,\text{Re}_{PC}}\right|_{\varpi}$ can be calculated with equation(5).

By finding the angle $\alpha$ which minimizes the error between slope of 'forbidden region' and slope of loop $L(j\omega)$, the PID parameters can be calculated as:

$$K_p = \frac{M_A}{M_P(j\varpi)\sqrt{1+F^2}} \tag{19}$$

$$T_d = \frac{F + \sqrt{F^2 + 1}}{2\varpi} \tag{20}$$

$$T_i = 4T_d \tag{21}$$

Application of the autotuner method to the steam/water loop, implies the following iterative steps.

*Step 1:* Select a loop and apply a sine test on the selected sub-loop while keeping other sub-loops work at operating points. From this test, obtain the magnitude and phase for the selected loop.

*Step 2:* Compute the PID parameters for the selected sub-loop.

*Step 3*: Apply the PID controller on the selected sub-loop. Perform sine test on another sub-loop, while keeping other sub-loops work at operating points.

*Step 4*: Repeat steps 2-3 for each loop until the output magnitude and phase do not change significantly between consecutive tests.

*Step 5*: After step 4 is completed, these are the final PID parameters obtained.

## 4. SIMULATION RESULTS

In order to validate the performance of the proposed method, other PID autotuners such as Åström-Hägglund (AH) (Åström and Hägglund, 1984), Phase Margin (PM) and Kaiser-Rajka (KR) are designed for steam/water loop. In the experiment, *GM*=2 and *PM*=45° are imposed for KC autotuning method.

**Table 2. PID Controller Parameters**

| Tuning method | Tuning method | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|---|
| AH | Sub-loop 1 | 1.97 | 55.26 | 13.82 |
| | Sub-loop 2 | 67.66 | 6.5 | 1.63 |
| | Sub-loop 3 | 41.63 | 3.15 | 0.79 |
| | Sub-loop 4 | 76.92 | 12.74 | 3.18 |
| | Sub-loop 5 | 88.76 | 7.04 | 1.76 |
| PM | Sub-loop 1 | 2.32 | 84.93 | 21.23 |
| | Sub-loop 2 | 79.73 | 9.99 | 2.5 |
| | Sub-loop 3 | 49.06 | 4.84 | 1.21 |
| | Sub-loop 4 | 90.65 | 19.58 | 4.9 |
| | Sub-loop 5 | 104.6 | 10.83 | 2.71 |
| KR | Sub-loop 1 | 2 | 77.94 | 19.49 |
| | Sub-loop 2 | 80.31 | 8.75 | 2.19 |
| | Sub-loop 3 | 15.23 | 7.70 | 1.93 |
| | Sub-loop 4 | 44.89 | 24.9 | 6.23 |
| | Sub-loop 5 | 63.17 | 13.74 | 3.43 |
| KC | Sub-loop 1 | 3.92 | 83.04 | 20.76 |
| | Sub-loop 2 | 204.17 | 8.12 | 2.03 |
| | Sub-loop 3 | 125.62 | 3.92 | 0.98 |
| | Sub-loop 4 | 232.12 | 15.88 | 3.97 |
| | Sub-loop 5 | 267.85 | 8.8 | 2.2 |

Table 2 shows the PID parameters obtained for every sub-loop with different tuning methods. Sub-loop 1 to sub-loop 5 indicate drum water level control loop, exhaust manifold pressure control loop, deaerator pressure control loop, deaerator water level control loop and condenser water level control loop respectively. There are two experiments to validate the performance of the proposed method. The first one is setpoint tracking experiment, and the other one is disturbance experiment. The setpoint and disturbance imposed to every sub-loop is shown in Table 3.

**Table 3. Parameters imposed in validation experiments**

| Output variables | Setpoint | Disturbance (Valve opening) |
|---|---|---|
| Drum water level | 1.5m | +30% |
| Exhaust manifold pressure | 0.125Mpa | -50% |
| Deaerator pressure | 27.5Kpa | +50% |
| Deaerator water level | 0.6m | +30% |
| Condenser water level | 0.42m | +30% |

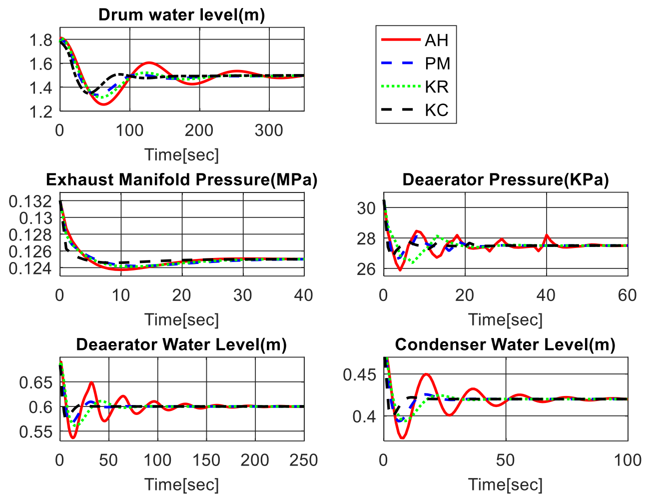


Fig. 3. System outputs in setpoint tracking with different PID controller.

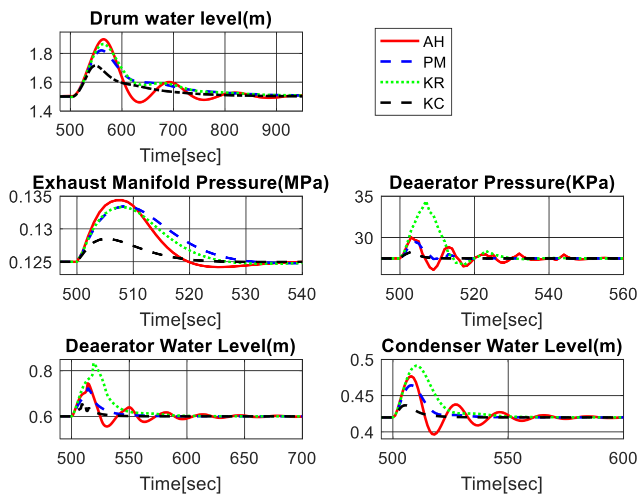


Fig. 4. System outputs in disturbance rejection with different PID controllers.

Fig. 3 and Fig. 4 show the control results in every sub-loop with different controllers. Fig. 3 indicates the setpoint tracking performance and Fig. 4 illustrates the disturbance rejection performance, respectively. From the results, the proposed method has a better performance not only in setpoint tracking but also in disturbance rejection in all sub-loops. Taking the interaction into account, the result of the whole steam/water loop with different autotuner PID controllers is shown in Fig. 5, the PID controller based on KC autotuner shows its superiority.

## 5. CONCLUSIONS

Steam power plant is one of the most important parts of the ship. Hence, to design an adequate controller for the steam/water loop is of great significance. However, the modeling process is difficult due to the complexity. In this paper, a PID autotuning method is proposed which is free to the system model. According to the system performance requirments, a “forbidden region” is defined on the Nyquist plane. Based on sine tests performed on the steam/water loop, PID controller is obtained. The performance of the PID controller based on KC autotuner is compared with other PID controllers. According to the simulation results, the proposed autotuning method obtains better results in all sub-loops not only in setpoint tracking but also in disturbance rejection.

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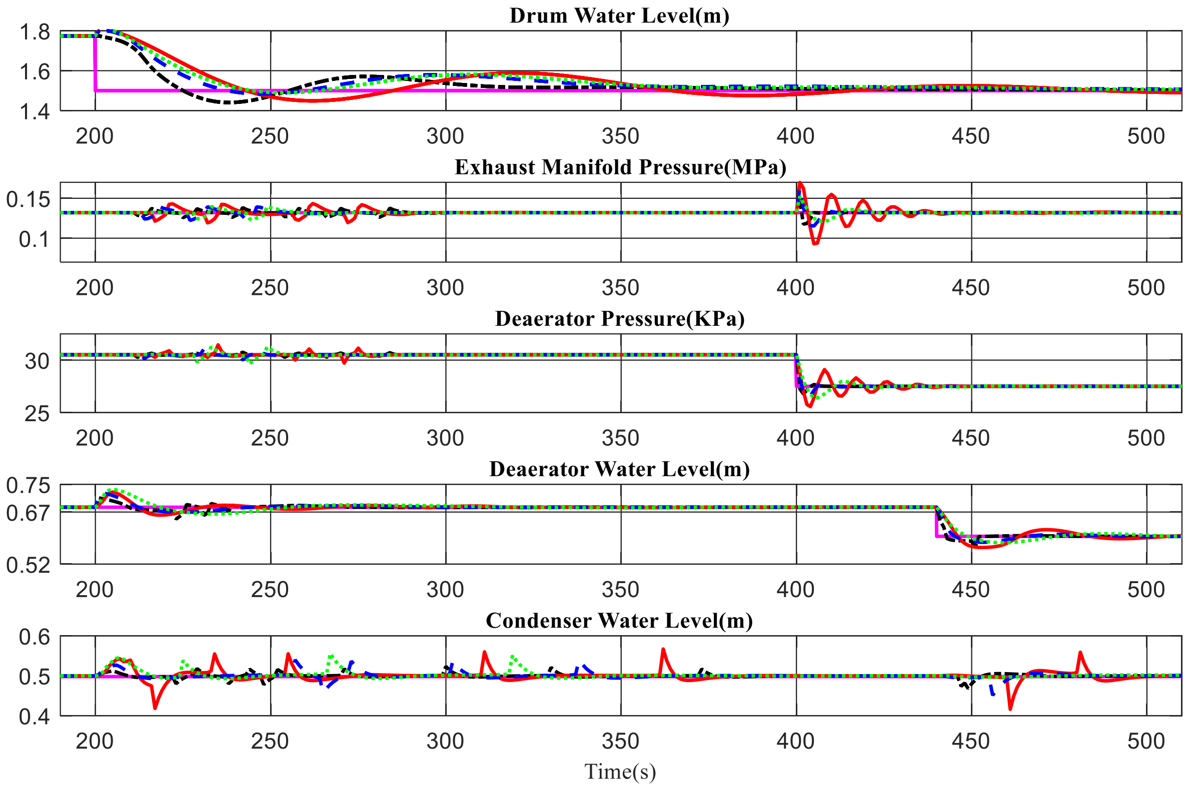


Fig. 5. System outputs with different controllers considering the interaction between sub-loops

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